The Effects of +Gz Loading Condition on the Human Heart

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Abstract

The computer modeling of the human body and its chemical, electrical and mechanical processes have many promising aspects. The present research is concerned with the finite element (FE) modeling the human heart in order to determine its response to large, positive gravitational accelerations (+Gz).

In order to produce realistic results for such an analysis, there are three fundamental criteria that need to be achieved: 1.) accurate material properties; 2.) exact geometry; and 3.) reasonable boundary conditions. Meeting these three specifications should result in a viable computer model. The present model contains stepping-stones to what would be considered an 'ideal' FE model if the above criteria were met. The model contains the complete left ventricle geometry and nonlinear material parameters.

The model was subjected to 1+Gz and 1.2+Gz accelerations to test the nonlinear material and nonlinear geometrical behaviour. The results show that the model can undergo large deformations in the nonlinear regime without failing.

Résumé

La modélisation mathématique du corps humain et de ses processus chimiques, électriques et mécaniques présentent des aspects prometteurs. La présente recherche concerne la modélisation par éléments finis du cœur humain en vue de déterminer la réponse de celui-ci à de grosses accélérations gravitationnelles positives (+Gz).

Pour qu'une telle analyse produise des résultats vraisemblables, il faut prendre en compte trois critères fondamentaux : 1) propriétés exactes des matériaux; 2) géométrie précise; 3) conditions aux limites. Ces critères remplis, on devrait obtenir un modèle mécanique viable. Le modèle actuel contient les pierres de gué pour arriver à ce qu'on considérerait comme le modèle éléments finis « idéal » si les critères susmentionnés était remplis. Il comporte la géométrie complète du ventricule gauche et les paramètres non linéaires des matières.

Le modèle a été soumis à des accélérations de 1+Gz et de 1.2+GZ pour tester le matériel non linéaire et le comportement géométrique non linéaire. Les résultats montrent que dans le régime non linéaire le modèle peut supporter de grosses déformations sans faillir.

Executive summary

In this project, a discretized Finite element model of the human heart, including left and right ventricles were developed. In this model geometrical and material nonlinearities were incorporated. The material nonlinearities were based on the available biaxial experiments on myocardium and were modelled using the Ogden strain energy function. Next the effects of +Gz acceleration was investigated, taking into account the changing constitutive properties of cardiac during the cardiac pre- and after loads. The results provide the level of deformation and stress due to the +Gz loading condition. Further, to improve the quality of the material model, a unique biaxial tensile machine was designed. This unit will be used in future research on this project to capture the material properties of the myocardium and pericardium used in the developed model.

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PART 1:

NONLINEAR FINITE ELEMENT MODELING OF THE HEART

1. INTRODUCTION

There is concern in the aeromedical field that high gravitational loads (+Gz) during flight adversely affect the functioning of the heart, i.e. to pump blood to the rest of the body, and may also damage the soft tissues due to increased stress levels. Verification of these stresses and any tissue damage has many associated difficulties since these would have to be measured invasively. It is therefore advantageous to develop a numerical method to provide insight into the damaging effects of +Gz loading.

Previous reports have focused on an extensive literature review and the addition of nonlinear material models to the previously developed left-ventricle geometry.

In this report, a FE model is created that more accurately represents the geometry of the human heart. The model is discretized in the pre-processing software package True*GRID*. The model was then exported to the FEA software MSC.MARC for analysis. Subsequently a nonlinear FEA was performed to test the capability of the new model.

2. GEOMETRY

The CAD model was composed of three surfaces that represent the exterior wall of the heart as well as the walls of the left ventricle/atrium and the right ventricle/atrium. This can be seen in Figure 1.

A number of components of the heart were not present or had to be removed. As can be seen in Figure 1, the CAD model contains none of the blood vessels that attach to the heart or the pericardial sac. The portions of the model which comprised the papillary muscles were removed since the valves of the heart were not present. Also because of the lack of a top surface to the CAD model the top portion of the model had to be trimmed for meshing purposes. Several anomalies in the CAD model were also present such as holes in the surfaces. These holes were required to be patched.

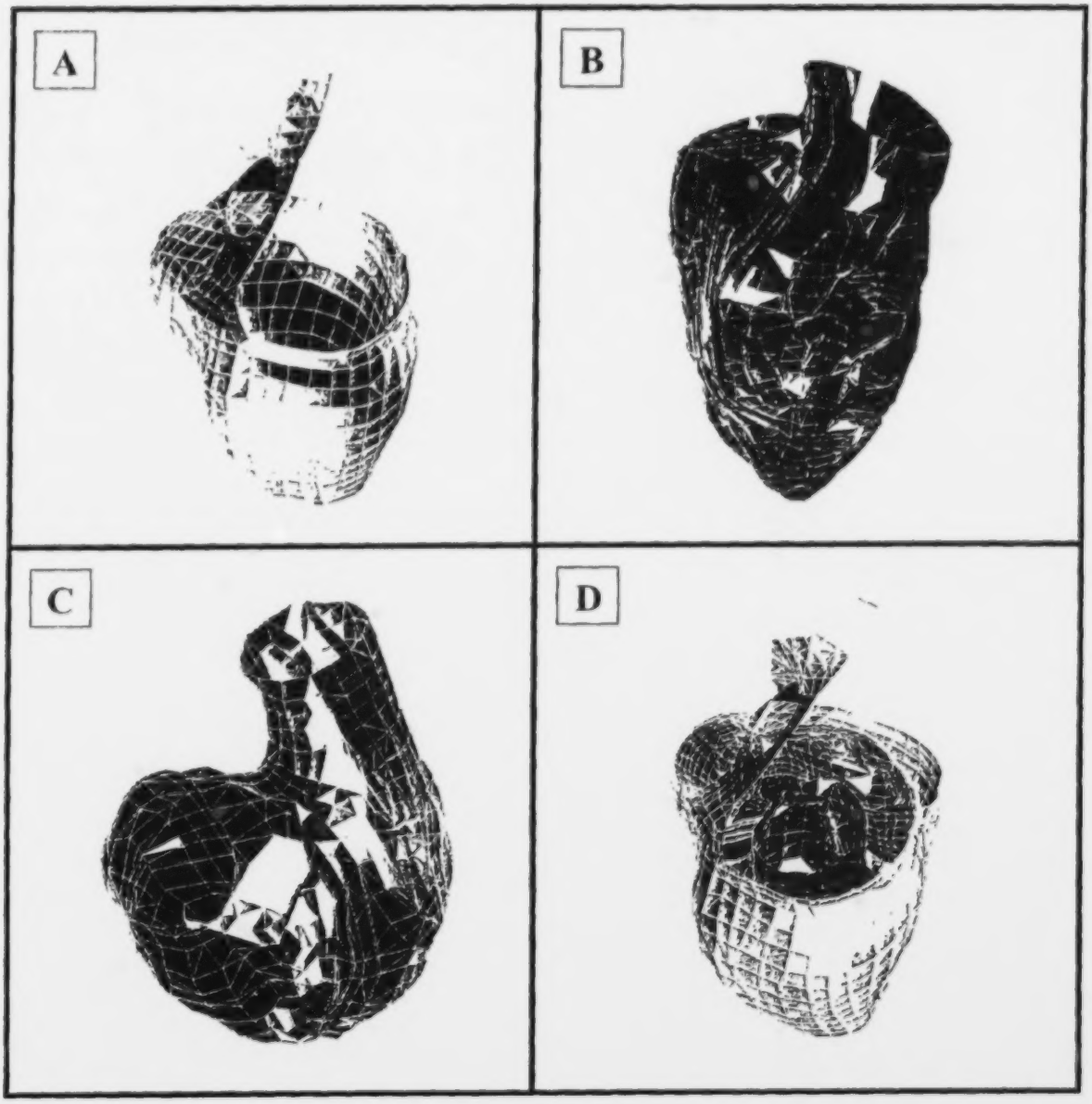

Figure 1: Surfaces of the CAD human heart model. A) Exterior surface, B) Left ventricle/atrium, C) Right ventricle/atrium and D) Complete surface model.

3. MESHING

3.1 TrueGRID Meshing Basics

The meshing of the left-right ventricle heart model was performed using the software package, True*Grid*. True*Grid* does not only generate the mesh, but builds the input file for numerous FEA codes. True*Grid* generates multi-block, structured meshes. Each block is composed of solid hexahedral (six-sided) elements and/or structural quadrilateral shell and beam elements arranged in rows, columns, and layers.
In True*Grid*, meshing an object is like how a sculptor molds a block of clay. The raw material in True*Grid* is a multiple block structured mesh.

The best meshes are based on structured blocks. Simulation codes are simpler and more accurate with block-structured meshes of good quality and important aspects of the mesh generation process work best on structured blocks (True*Grid* Manual, 2001). The following gives a brief explanation of meshing in True*Grid*.

Step 1: Defining the Block Mesh

The first step is to define the block mesh (see figure 2). This mesh is located in an artificial region known as the "Computational Space." Upon generation of this block mesh, a mesh is automatically created in the "Physical Space." The physical space is where your actual geometry, i.e. CAD part is contained. In the computational space, the mesh never becomes distorted so that the user always has a reference to the moulded mesh in the physical space.

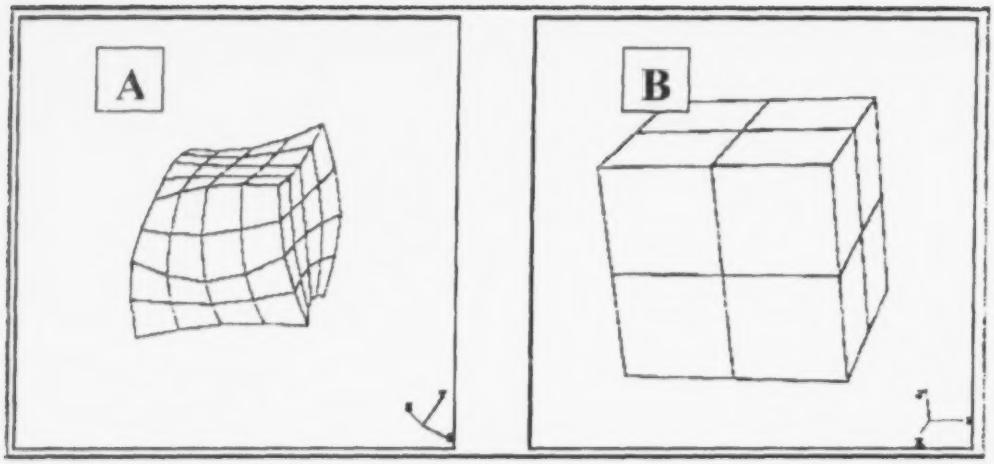

Figure 2: A) Physical mesh of the block. B) Computational mesh of the block with 8 subBlocks. From Trug*Grid* Manual, 2001.

Step 2: Shaping the Mesh

True*GRID* allows the user to manipulate the mesh in almost any way imaginable. Every vertex of a block can be moved to a desired location using interactive techniques, or attached to lines and points of surfaces that define the geometry. The mesh can also be manipulated using transformations such as translations, rotations, mirroring, etc.... However, in the case of the heart, in which the geometry is so complex, the only way to capture the shape of the surfaces is to use a method known as "projection." The projection method is a collection of techniques used to place nodes of the mesh onto surfaces. In this way, a more accurate representation of the hearts surface can be attained. When a node of the mesh is projected onto a surface, it is moved to the point on the surface that is closest to the initial position of the node. It may be necessary to project a node onto two surfaces simultaneously. This is commonly the case for nodes along an edge of the block mesh. True*Grid* automatically detects this condition and projects the node to the closest point on the intersection of the two specified surfaces. The illustrations in figure 3 show a simple case of the projection method in which a block mesh is projected onto two cylindrical surfaces.

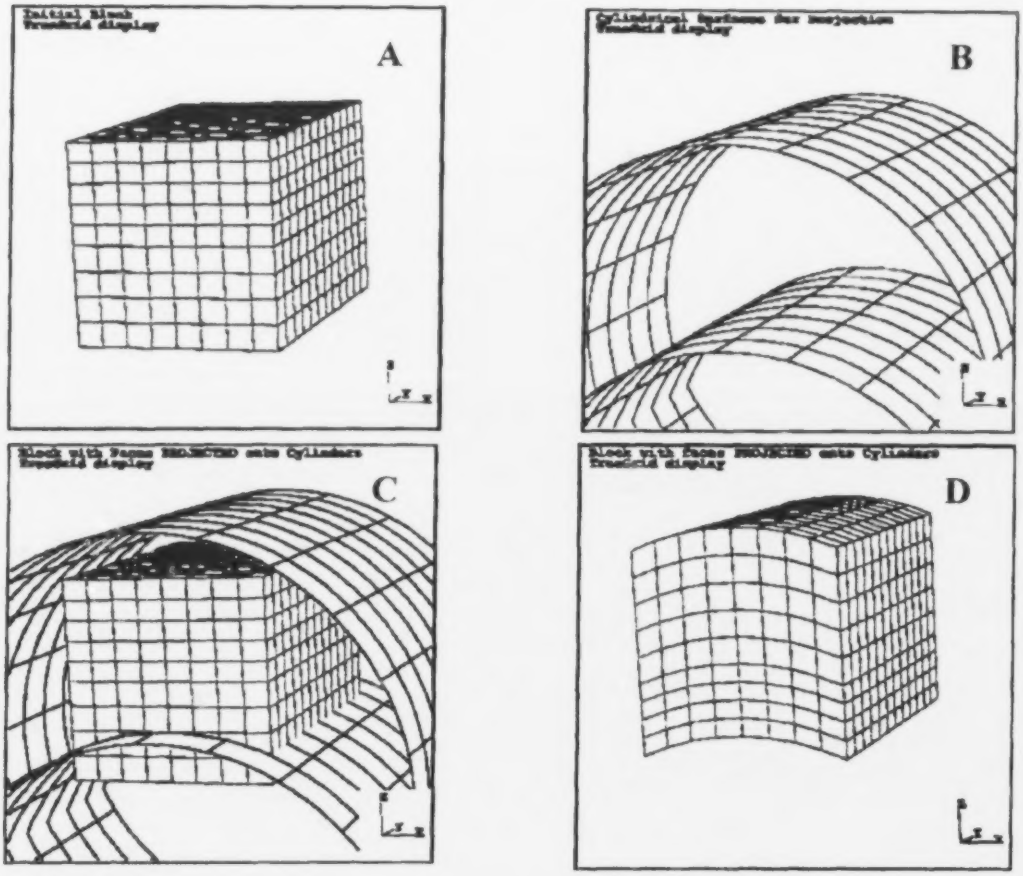

Figure 3: A) Simple part before projections. B) Cylindrical surfaces. C) Simple block and cylindrical surfaces. D) Projection of block faces onto cylindrical surfaces. From True*Grid* Manual, 2001.

Step 3: Mesh Refinement

Once the basic mesh is molded to the shape of the model, the mesh needs to be smoothed out to better fit the geometry and to reduce the amount of distortion in the elements. One way to do this is to increase the number of elements in the mesh. Since the blocks in the computational mesh represents regions of the mesh in rows, columns and layers, it is easy to add elements to the regions that require more elements to accurately define the geometry. This is accomplished by using the "mseq" command,

which adds elements to the specified region. Subsequently a linear interpolation scheme is implemented that linearly spaces out the nodes in the mesh where the elements have been added. Figure 4 represents a tri-linear interpolation to position the interior nodes of the region. This interpolation is based on the positions of the nodes along the faces of the region. These face nodes are not moved; neither are the edge nodes of the region. In addition to linear interpolation, there are other interpolation schemes available to redistribute the nodes in order to attempt to create a smoother finish to the mesh.

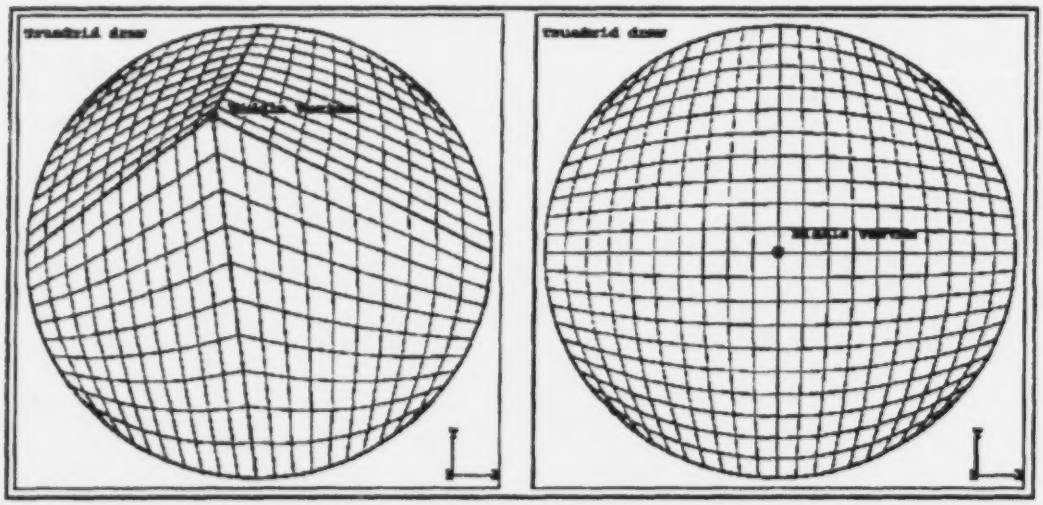

Figure 4: Interpolation of block face. From True*Grid* Manual, 2001.

3.2 The Meshed Heart

Using the techniques discussed above, a solid meshed model containing the left and right ventricle of the heart was developed. The finished model is comprised of approximately 16536 hex elements resulting in about 61485 degrees of freedom. Figure 5 shows the completed mesh. The final meshed heart was composed of 6 block parts merged together using specialized transition elements found in True*GRID*. These transition elements are required in order to prevent the elements at the bottom of the model from becoming excessively small and in turn to decrease the number of elements in the mesh reducing computational time. Because of the large curvature and internal

chambers, it is difficult to obtain a completely smoothed mesh even with interpolation since using interpolation techniques can cause distortion of the mesh in other areas. This is the reason why some the elements on the surface may be slightly skewed. However internal elements are less distorted.

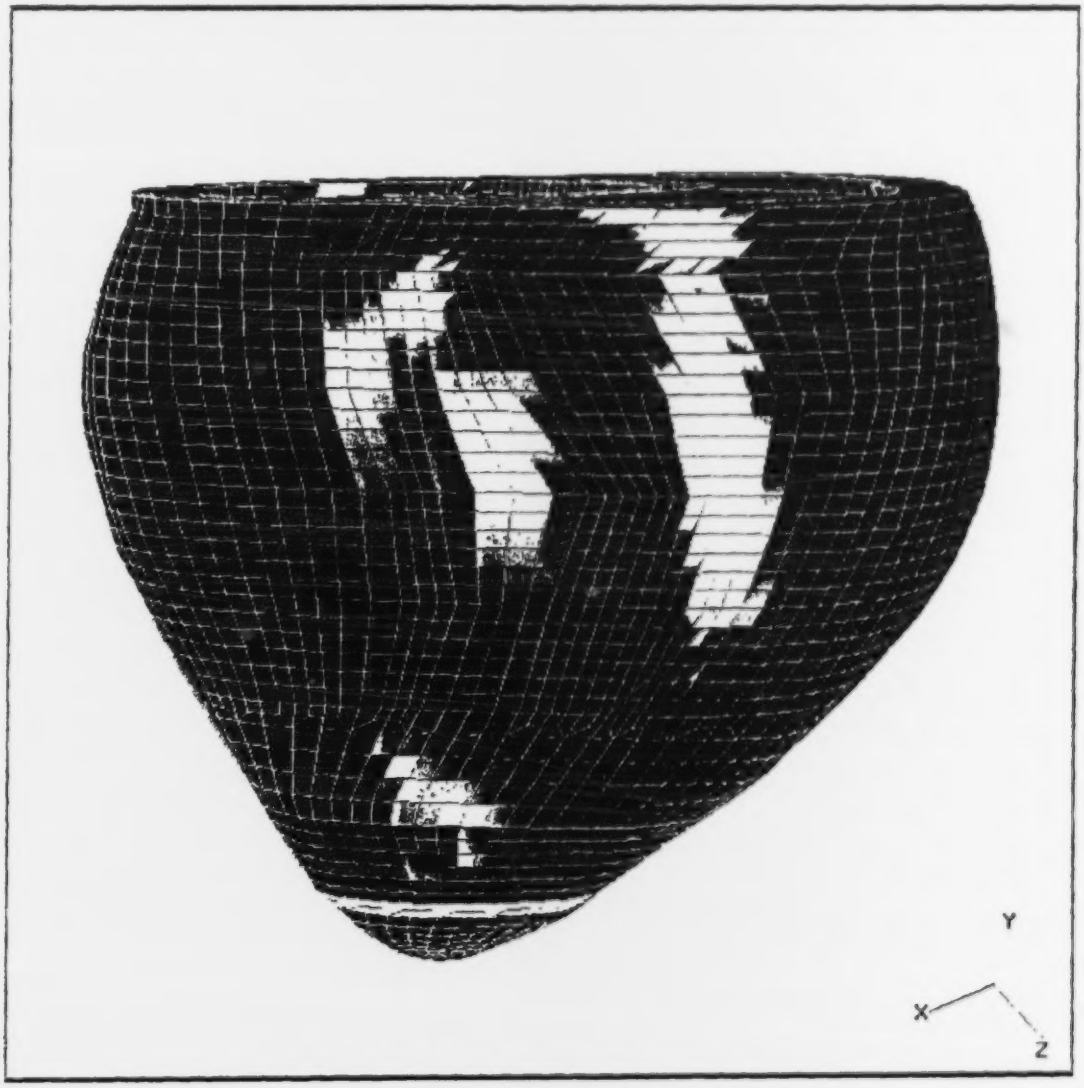

Figure 5: Mesh of the left-right ventricle model of the human heart.

The following pictures (figure 6) show the individual block parts that comprise the two-ventricle heart model. Figure 6-D shows a clear view of the transition elements.

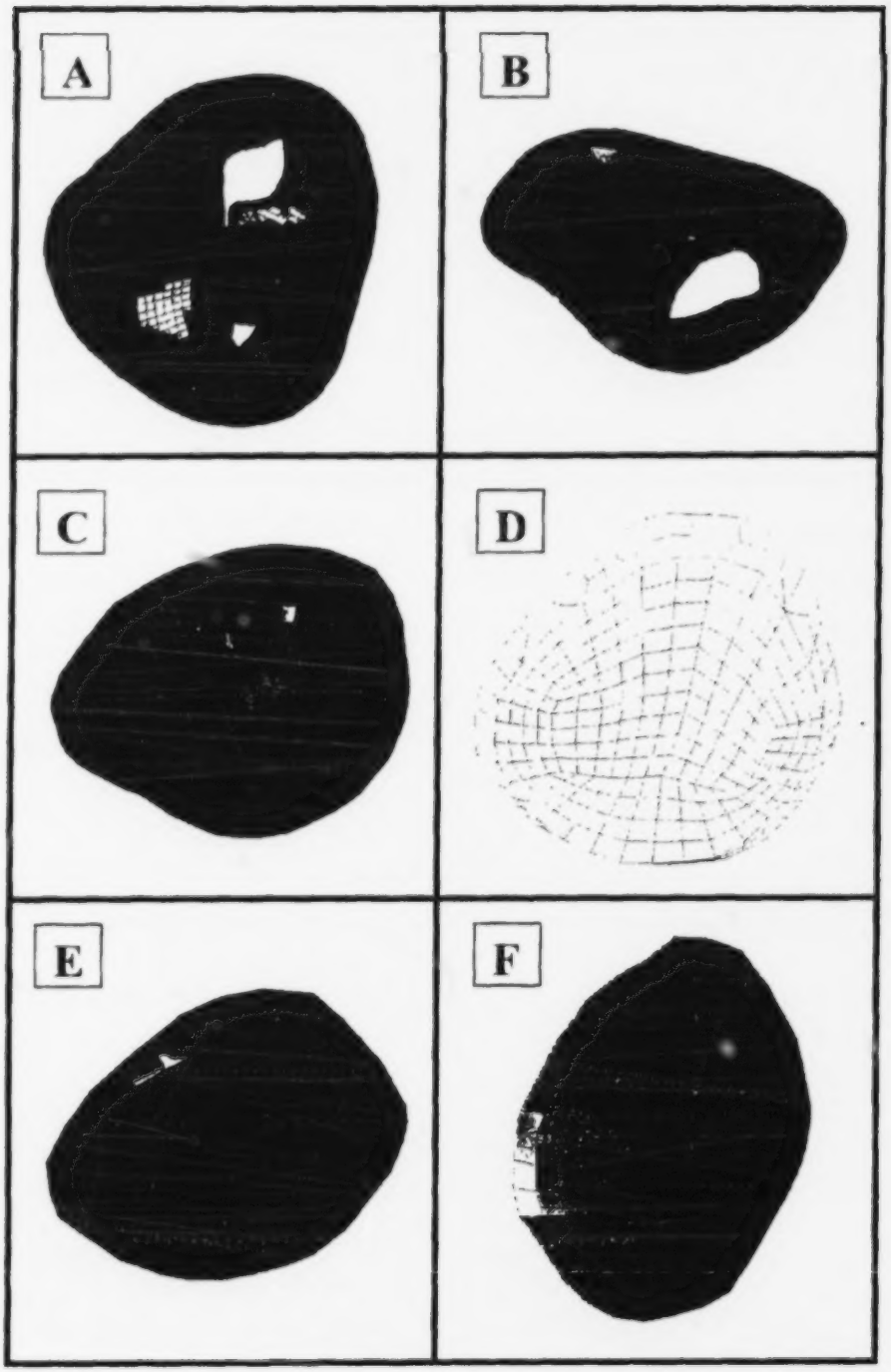

Figure 6: The six blocks comprising the heart model.

Upon completion of the discretization of the model, the model was imported into the commercial nonlinear FE package MSC.MARC. A check of the mesh in MSC.MARC showed no defective elements, which can be prevalent when dealing with such complex geometry.

4. FINITE ELEMENT ANALYSIS

4.1 Element Selection

A nine-node, isoparametric, three-dimensional brick element with tri-linear interpolation was the element of choice for this application in MSC.MARC. This hex element is shown in figure 7. Eight of the nodes are used for displacement and geometry representation. A single node located at the center of the brick is used for hydrostatic pressure for modeling incompressible materials such as elastomers. This element is specifically formulated for such materials and is a required element type for the Ogden material model.

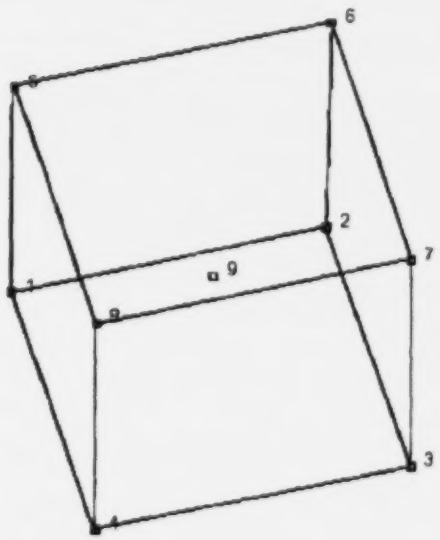

Figure 7: Element 84. From MSC.Marc, 2000.

4.2 *Boundary Conditions*

In this FE analysis, the heart was again suspended from the top. Obviously this type of fixed condition is not a good representation of the true conditions present in the body; however the purpose of this analysis was not to impose new boundary conditions, but rather to test the adequacy of the left-right ventricle heart model. The ease of application of this boundary condition makes it ideal for this analysis, plus it also gives insight into the capability of the nonlinear material model. The figure below shows how the model was constrained. A gravity load of 1.5 +Gz in the negative y-direction was also applied to the model.

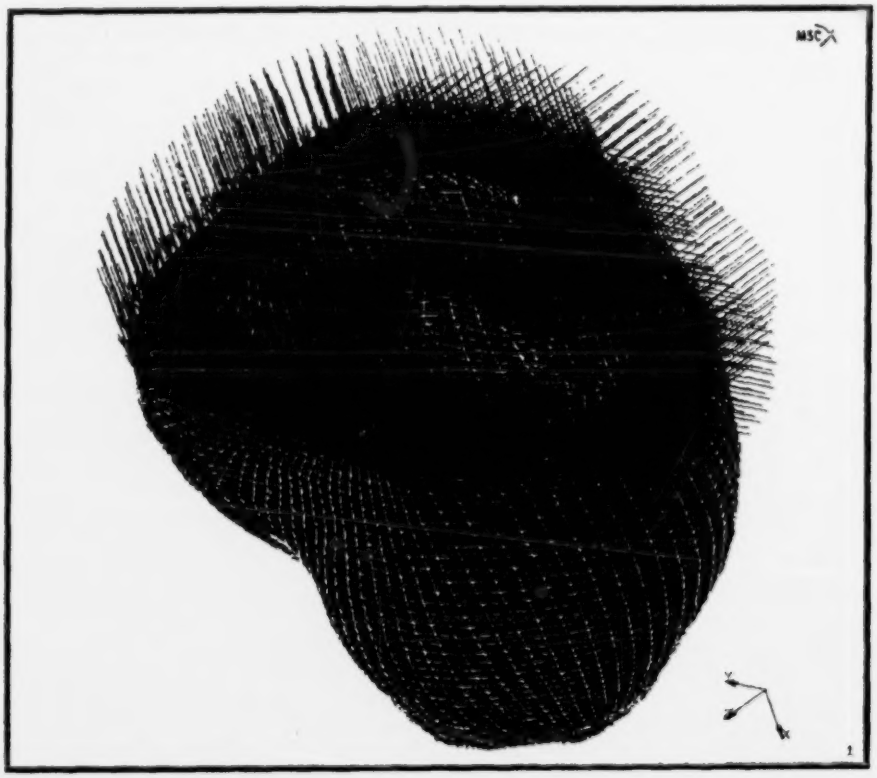

Figure 8: Meshed heart model showing fixed boundary constraints at top of model.

4.3 Material Properties

Material models, such as those for elastomers and soft tissues, are generally characterized by a strain energy (density) function. Materials such as these are known as hyperelastic. Implicit in the use of these functions is the assumption that the material is isotropic and elastic.

The present tissue model incorporates a nonlinear hyperelastic material model developed by Ogden (1984) for slightly compressible elastomers. The strain-energy function is given as:

$$W = \sum_{n=1}^{N} \frac{\mu_n}{\alpha_n} J^{\frac{-\alpha_n}{3}} \left(\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3\right) + 4.5K\left(J^{\frac{1}{3}} - 1\right)^2$$

Where μ_n and α_n are moduli and exponential material constants respectively

K is the initial bulk modulus

J is the Jacobian (volumetric ratio), defined by $J = \lambda_1\lambda_2\lambda_3$

λ_i are the principle stretch ratios

N is the number of terms.

Exact incompressibility means the material exhibits zero volumetric change (isochoric) under hydrostatic pressure. In the case of perfectly incompressible material, $\lambda_1\lambda_2\lambda_3 = 1$ and the pressure in the material is not related to the strain in the material. It is an indeterminate quantity as far as the stress-strain relationship is concerned or in other words another degree of freedom. If we were to consider a Hookean material, defining a Poisson's ratio of 0.5 would result in incompressible material behaviour. Data from Humphrey (1987) (figure 10) was fitted to the Ogden model above to represent the nonlinear behaviour of cardiac muscle. This resulted in the following parameters using a three term fit (Table 1).

μ_1	1.52085E-07	[N/cm^2]	α_1	7.25511
μ_2	4.57005E-01	[N/cm^2]	α_2	21.7307
μ_3	2.20879E-06	[N/cm^2]	α_3	11.2035

Table 1: Ogden material parameters from fit to myocardial data using MSC.MARC.

This fitting also resulted in a bulk modulus of 24827.7 N/cm^2. The density of the tissue was given as 1.045 g/cm^2.

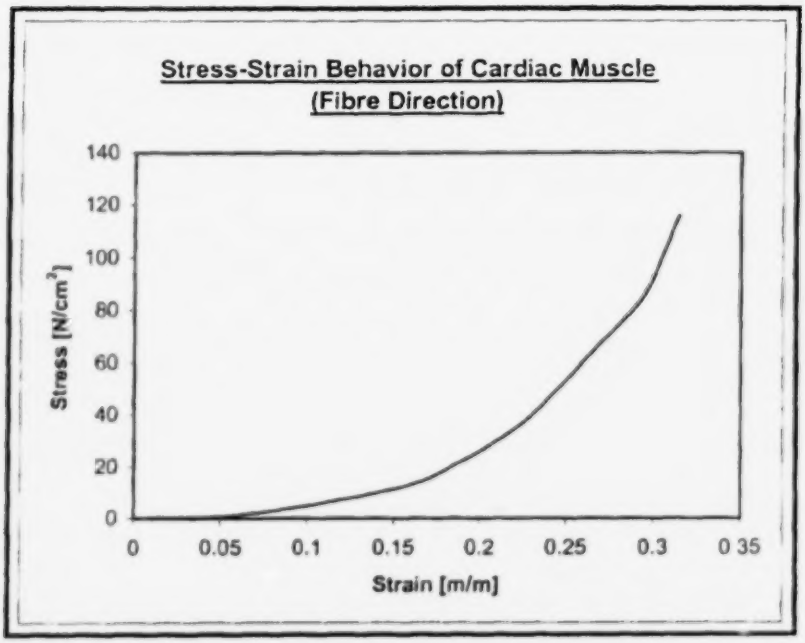

Figure 9: Stress-strain properties of myocardium (modified from Humphrey, 1987)

4.4 Solution Procedures

The following solution procedures were used in the analysis:

- Large Displacement
- Total Lagrangian Method
- Full Newton-Raphson
- Solver: Direct Sparse
- Adaptive Loading: Modified Riks-Ramm
- Automatic Time Step Cut Back

5. FINITE ELEMENT RESULTS

The nonlinear analysis of the heart model took approximately four hours on a Sun Ultra 60 workstation. Using adaptive loading and automatic time step cutback, the solution converged in 8 increments. Figure 10 below shows the y-displacement of the heart under 1.5 +Gz of acceleration. This resulted in a maximum downward displacement of -2.713 cm. This also resulted in a maximum equivalent strain value of 51.27 % (see figure 11). The equivalent strain is a measure of the average strain in the element.

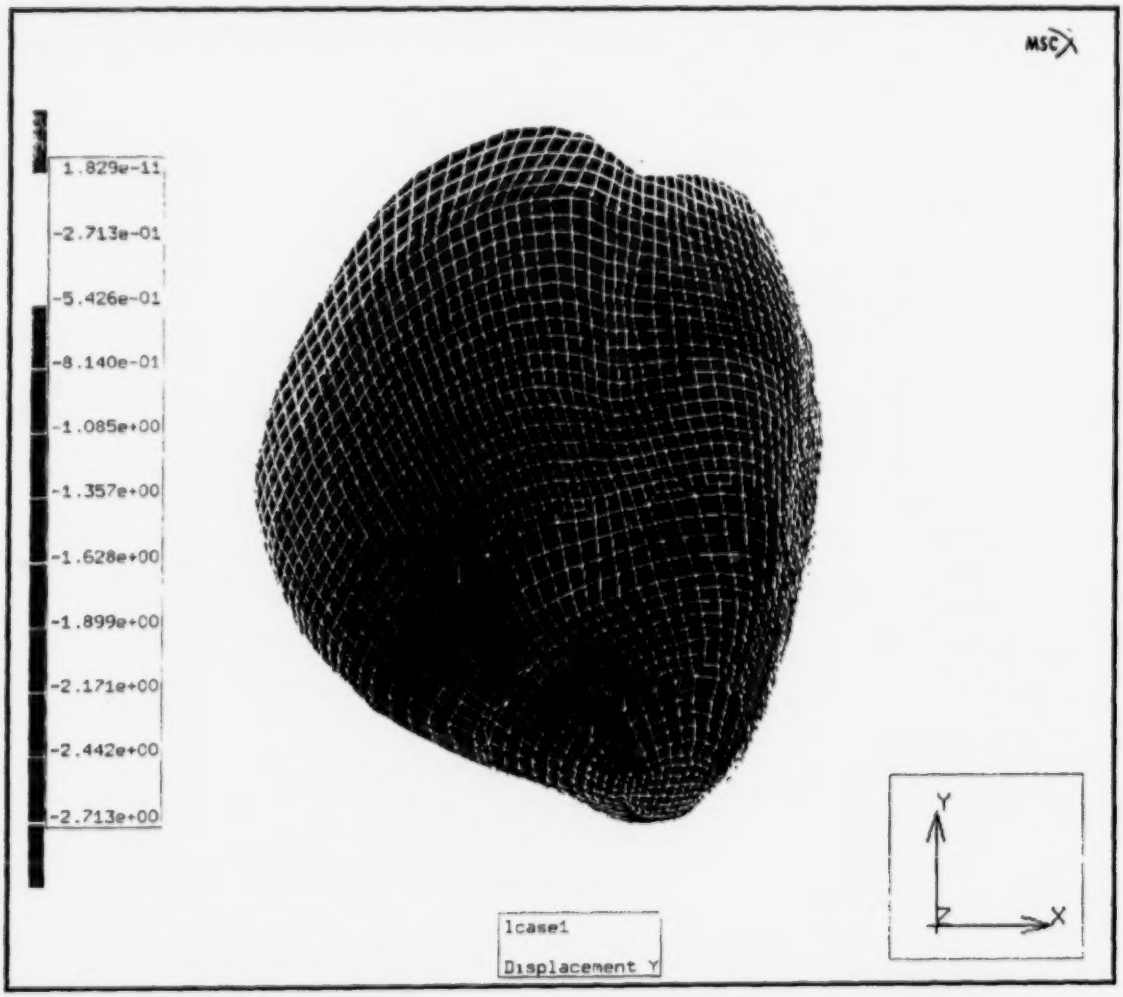

Figure 10: Y-displacement under 1.5 +Gz. Displacement measured in [cm].

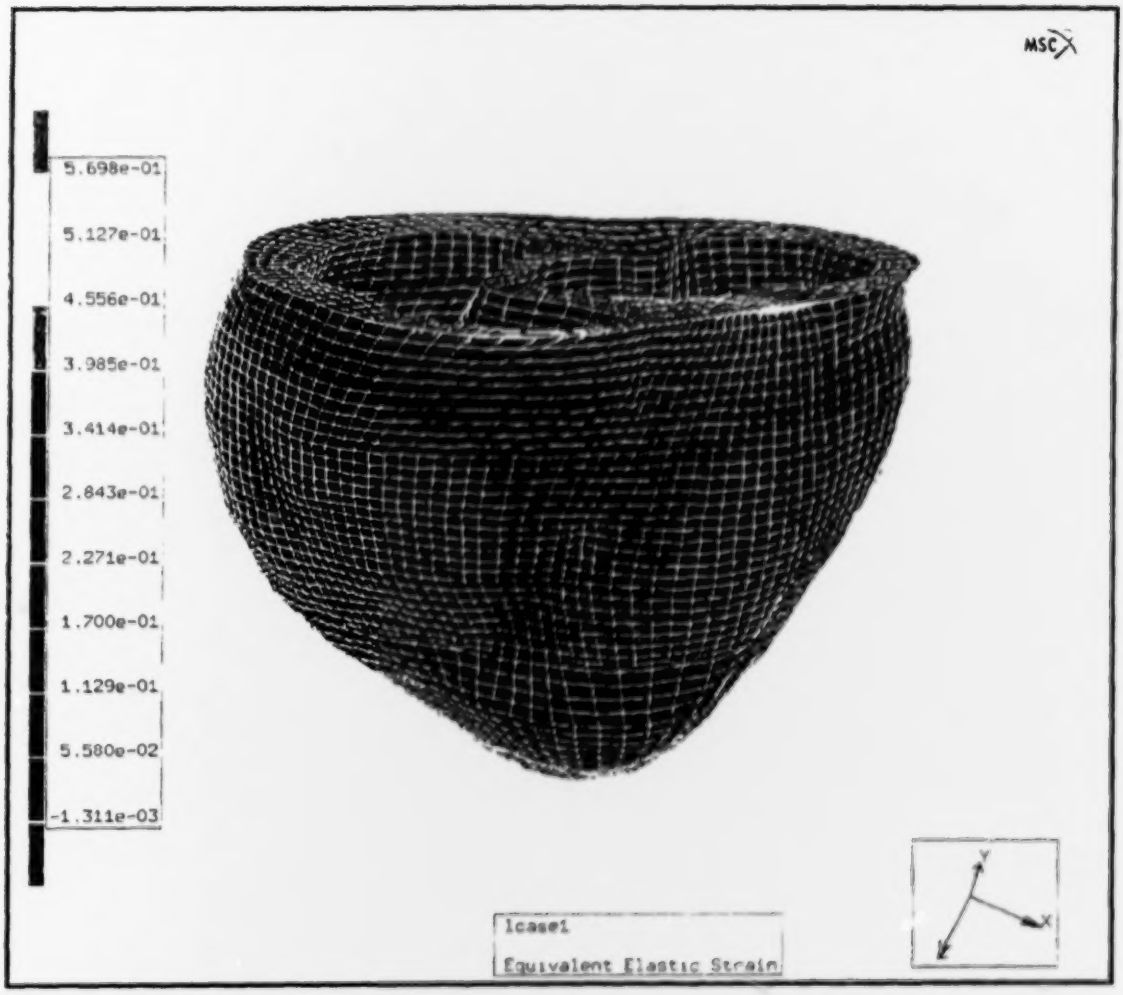

Figure 11: Equivalent elastic strain under 1.5 +Gz.

6. CONCLUSION AND FUTURE WORK

A more accurate geometric model of the male human heart has been presented. This model contains both the left and right ventricles as well as portions of the left and right atria. It has been shown that this new model can successfully undergo large deformations, without failure of the mesh. However, even larger displacements are possible with the inclusion of adaptive

mesh refinement in which overly distorted elements are refined. This will be incorporated in the analysis as it becomes necessary to do so.

Future plans for the project are to implement the following:

- Minor adjustments to meshed heart:
    - Addition of left and right atria
- Orthotropic material properties
- Improved boundary conditions

Part 2

EXPERMENTAL TESTING APPARATUS

8. COMPONENTS

The apparatus consists of the following key components:

- 4Linear bearings
- 4 T-shaped grips
- 2 Load cells with 0.05lb resolution
- Left-handed/right-handed threaded rod assembly
- 2 DC servomotors and bearing supports.

9. FUNCTIONALITY

A Data acquisition unit with digital I/O card made by National Instruments (DEK-10) controls the apparatus. The unit is capable of performing creep compliance, stress relaxation and uniaxial/biaxial tensile tests. The servomotor has 35 ft-lb of torque capacity and is controlled by signalling an optical encoder via digital input/output cards. Displacement control is achieved by calibrating the lead screw advancement with respect to the number of steps that the encoder moves. Adjusting the optical encoder speed controls the loading rate. In other words, the optical encoder is the primary means for controlling the strain rate and maximum strain magnitude. This controlling method provides a desirable environment for stress relaxation testing where the displacement is required to remain constant. The load transducer, in this instance, only acts as a data collection unit. In the case of a creep compliance test, the load transducer signal is used to control the test as well as to collect data. However, the loading rate is always controlled by the optical encoder thus, it provides the flexibility to perform various loading rate tests. The following is the detailed and assembly drawing of the apparatus.

Figure 12 is the assembly drawing of the apparatus. Figures 13 and 14 show the detailed drawings of the components. Figures 15 and 16 show pictures of the actual testing apparatus and data acquisition unit.

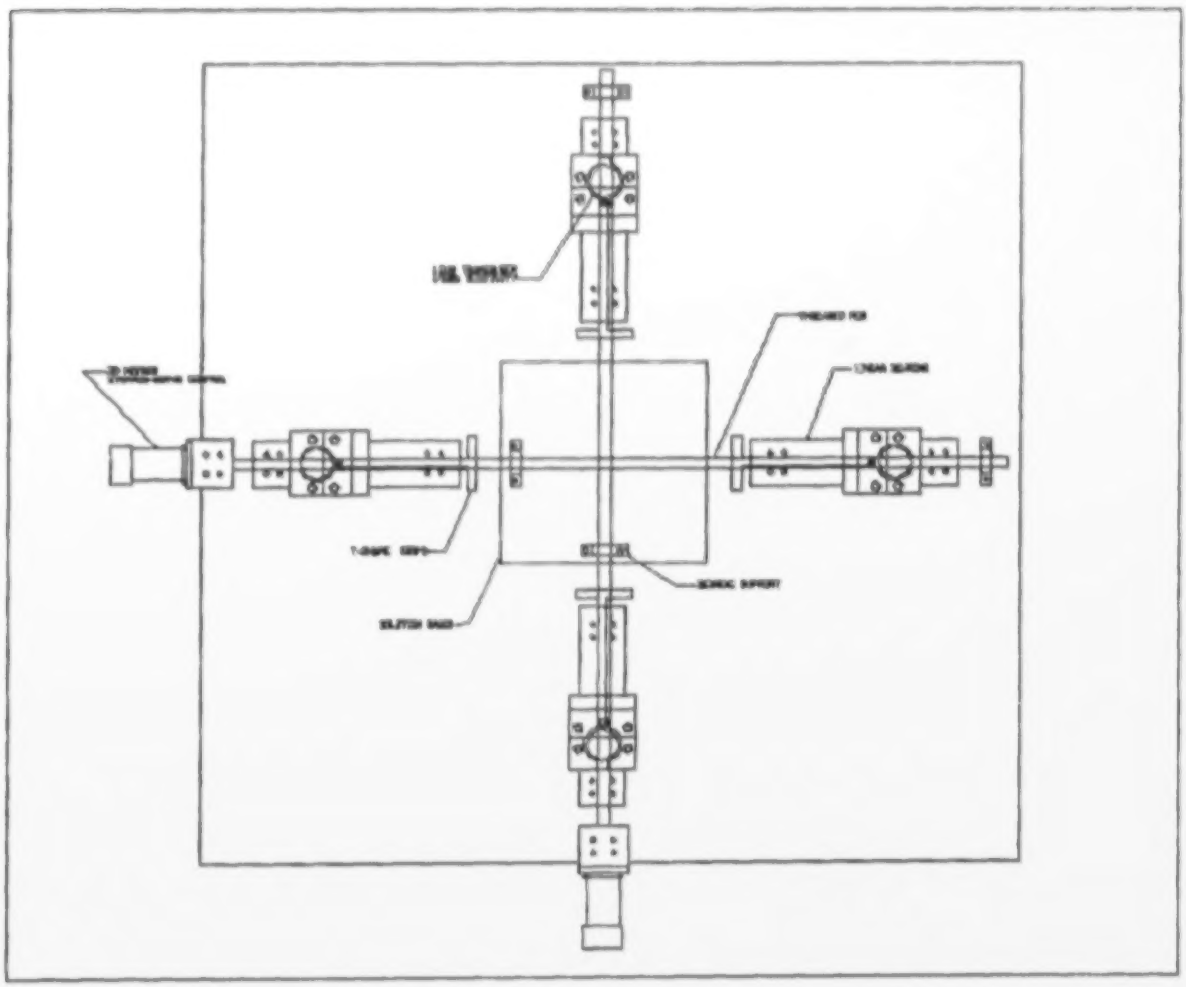

Figure 12: Assemby Drawing.

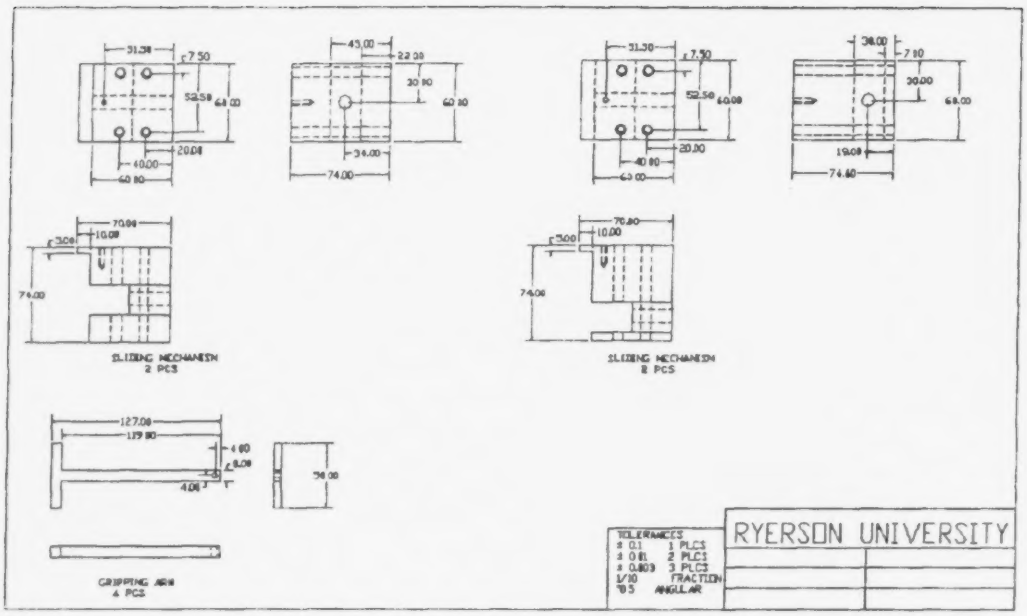

Figure 13: Detail Drawing 1.

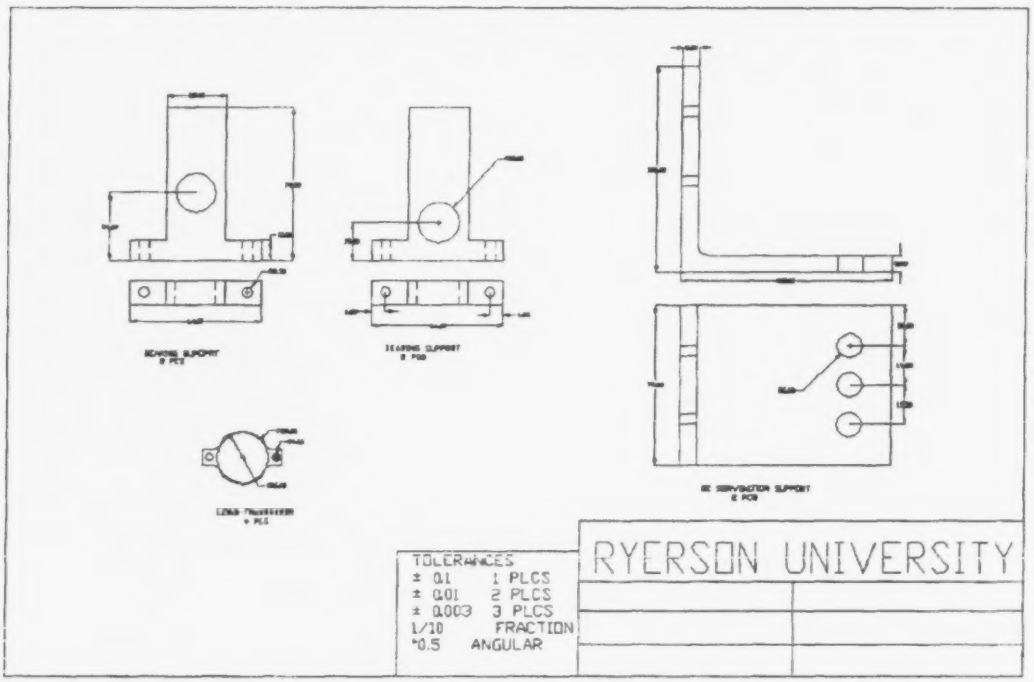

Figure 14: Detail Drawing 2.

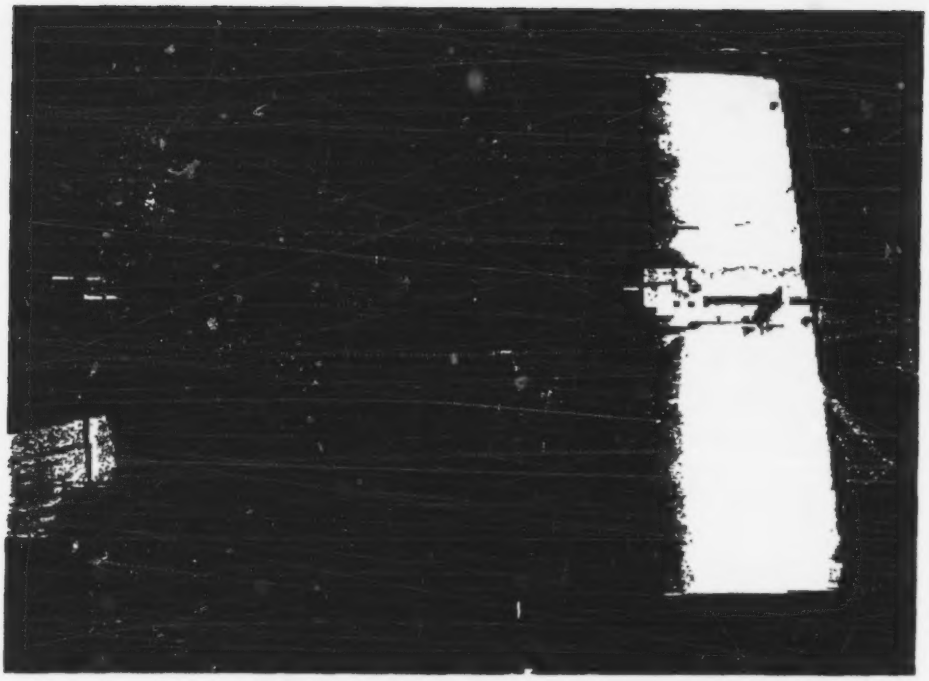

Figure 15: Biaxial Testing Apparatus.

Figure 16: Biaxial Testing Apparatus with Data Aquisition Unit.

The limitation of the experimental apparatus is that the displacement of the test spesimen mearured from optical encoder is the average displacement in the sample. In order to evaluate the displacement at the center of the test specimen, a CCD camara and a videa capture card are needed. The CCD camera with minimum 60 frame per second and a video capture card with comparable speed has to be added to the apparatus.

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14. ABSTRACT

(U) The computer modeling of the human body and its chemical, electrical and mechanical processes have many promising aspects. The present research is concerned with the finite element (FE) modeling the human heart in order to determine its response to large, positive gravitational accelerations (+Gz). In order to produce realistic results for such an analysis, there are three fundamental criteria that need to be achieved: 1.) accurate material properties; 2.) exact geometry; and 3.) reasonable boundary conditions. Meeting these three specifications should result in a viable computer model. The present model contains stepping-stones to what would be considered an 'ideal' FE model if the above criteria were met. The model contains the complete left ventricle geometry and nonlinear material parameters.
The model was subjected to 1+Gz and 1.2+Gz accelerations to test the nonlinear material and nonlinear geometrical behaviour. The results show that the model can undergo large deformations in the nonlinear regime without failing.

(U) La modélisation mathématique du corps humain et de ses processus chimiques, électriques et mécaniques présentent des aspects prometteurs. La présente recherche concerne la modélisation par éléments finis du cœur humain en vue de déterminer la réponse de celui-ci à de grosses accélérations gravitationnelles positives (+Gz).
Pour qu'une telle analyse produise des résultats vraisemblables, il faut prendre en compte trois critères fondamentaux : 1) propriétés exactes des matériaux; 2) géométrie précise; 3) conditions aux limites. Ces critères remplis, on devrait obtenir un modèle mécanique viable. Le modèle actuel contient les pierres de gué pour arriver à ce qu'on considérerait comme le modèle éléments finis « idéal » si les critères susmentionnés était remplis. Il comporte la géométrie complète du ventricule gauche et les paramètres non linéaires des matières.
Le modèle a été soumis à des accélérations de 1+Gz et de 1.2+GZ pour tester le matériel non linéaire et le comportement géométrique non linéaire. Les résultats montrent que dans le régime non linéaire le modèle peut supporter de grosses déformations sans faillir.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) +Gz, Human Heart, Effects of +Gz

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